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Economics of $F_{0.1}$

Economic and Commercial Analysis
Report No. 18

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Economics of $F_{0.1}$

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ABSTRACT

This paper discusses the setting of total allowable catch amounts (TACs) using the $F_{0.1}$ fishing mortality criterion. The economic impacts of adjustments to fishing mortality rates on the harvesting sector are of primary interest. The background of $F_{0.1}$ including its appearance as the reference point for establishing TACs, its theoretical underpinnings and its assumptions and pitfalls are discussed. A single species model framework is described which explores the interrelated dynamic resource stock and economic impacts of fishing mortality management (including the $F_{0.1}$ criterion) under particular situations, e.g. of stock growth and recruitment.

RÉSUMÉ

On discute, dans le présent article, de l'établissement des valeurs du total des prises admissibles (TPA) lorsqu'on utilise le critère $F_{0.1}$ de mortalité due à la pêche. Les répercussions économiques du rajustement des taux de mortalité due à la pêche sur ce secteur d'activités présentent le plus grand intérêt. On parle ensuite du contexte qui a mené à $F_{0.1}$, notamment de son utilisation comme pointe de référence pour fixer les TPA, de ses fondements théoriques ainsi que de ses trétentions inconvénients. On fait aussi la description d'un cadre de modèle établie pour une seule espèce dans laquelle on examine le stock de ressources dynamiques en interrelation et les répercussions économiques de la gestion de la mortalité due à la pêche (y compris le critère $F_{0.1}$) dans cette situations, par ex. de la croissance des stocks et du recrutement.

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Economics of $F_{0.1}$

Introduction

The purpose of this paper is to discuss current strategies for the management of Canadian commercial fisheries which set total allowable catch amounts (TACs) using the $F_{0.1}$ fishing mortality criterion. Of particular interest are the economic impacts on the harvesting sector of this strategy and alternative fishing mortality rates.

The background to $F_{0.1}$ including its appearance as the reference point for establishing TACs are presented along with its theoretical underpinnings and its assumptions and pitfalls. Alternative theoretical reference points for establishing TACs are also discussed. A model framework is described which examines dynamic effects of using $F_{0.1}$ under particular situations, e.g., of stock growth and recruitment. Model results provide evaluation of the limited fishing mortality regulation strategy linking the biological elements to the economic elements of the fishing sector. For purposes of illustration, a simple version of the model is presented using data based broadly on the Newfoundland nearshore (3KL) northern cod fishery.

Fisheries Management and $F_{0.1}$. The Fisheries Act, first enacted in 1868 provides the mandate to the Department of Fisheries and Oceans regarding fisheries management in Canada. Broadly stated, the basis of federal fisheries policy and management for the last 120 years are specified in the policy goals of: (i) conservation of fish resources; (ii) development of commercially viable Canadian fisheries; and (iii) distribution of fish resources among Canadians who benefit from these resources (Laubstein 1987).

Actual operational strategies depend on the existing state of the marine resource and its habitat, and the current development of the commercial fishery. In particular, conservation measures for all individually managed commercial stocks on the Atlantic coast (with the exception of lobster, Atlantic salmon, and some crab stocks) currently take the form of allowable harvesting up to a preset maximum tonnage over an annual harvesting period. This maximum harvest is known as the Total Allowable Catch or TAC. Assuming some prior knowledge about the existing size of the resource stock, (e.g., by numbers of pieces or total biomass weight) the TAC may be expressed as a (continuous) rate of mortality due to fishing, denoted F. While reference points for determining the actual TAC for individual species may vary, most commercial fish stocks on the Atlantic coast currently use the $F_{0.1}$ fishing mortality criterion.

To define $F_{0.1}$, consider the commercial exploitation of a single species by only one fisherman and a single vessel. The level of fishing of the fisherman in a fixed period (e.g., each year) may be described by the percentage of the total harvestable stock that is captured (also referred to as the exploitation fraction or the fishing mortality rate). Now, if new (standardized) vessels are attracted year after year into this fishery, then the results will be higher total fishing effort, and–depending on the current level of exploitation of the stock and its growth characteristics–higher total annual catch by the fleet. However, at some point the increasing numbers of vessels will begin to have significant effects on stock abundance. Beyond this point, fishermen will find that it requires more fishing effort to capture the same amounts as in previous years, or in other words, that their catch per unit of fishing effort is decreasing with time. As still more vessels join the fleet, total annual catch may continue to increase–but by smaller and smaller amounts each year–and the new vessels may actually catch wholly at the expense of vessels that had joined the fleet in previous years.

In this context, the $F_{0.1}$ level of fishing mortality can be described as that point where another unit of fishing effort, e.g., adding another vessel to the commercial fleet, will result in an increase in total annual catch per vessel which is only 10% as large as the average

annual catch made by the lone fisherman who had exploited the stock as the sole vessel operating in the fishery. For a given commercial species, $F_{0.1}$ is determined from biological charactersitics of the stock, including natural survival rates and dynamic growth patterns. Finally, information from stock assessments provides the base to which the $F_{0.1}$ mortality rate is applied to obtain the total allowable catch for the commercial fleet for the year.

Canadian commercial fisheries management on the Atlantic coast calculate annual TACs by species using the $F_{0.1}$ criteron. The TAC is then subdivided into specific quotas and/or enterprise allocations for the various components of the Canadian commercial fleet (including the 'inshore' and 'offshore' fleets by gear and area) and possibly, for foreign vessels. The resultant system of annual quotas establishes a specific management plan which is put into effect and monitored for the current season (e.g., Atlantic Groundfish Management Plan, Canada 1988). Information obtained from actual harvesting patterns and annual stock assessments throughout the season provide the data required to update and monitor the current management plan, and to prepare new plans for future years.

Historical Context of $F_{0.1}$. In the early 1960's the International Commission for the Northwest Atlantic Fisheries (ICNAF) responded to mounting pressure on some fish stocks (due primarily to over-harvesting) by introducing controls on the minimum mesh sizes used for net captures. The theory behind this regulation had been developed earlier by Beverton and Holt(1957) in a landmark piece of scientific research. Their work provided an objective, biologically-based means of implementing conservation measures for some stocks. Moreover, as justification for their methods, one of the major 'selling points' was that the approach 'caused fewer problems than direct control of the amount of fishing' (Canada 1987).

By the late 1960's however, it became evident the mesh size regulations suggested by Beverton and Holt's method were not sufficient to curb depleting stock effects, and fishing controls in the form of direct total quotas (TAC's) were introduced. Because of the direct effect of TAC schemes on fishing, there where problems with setting the appropriate size

of the 'global quota'. As one means of reducing problems of economic allocation among the fleet, it was deemed desirable to set the TAC based on 'objective biological criteria'. Simplified models of populations dynamics (e.g., Schaefer's logistic model) were used to establish fishing mortalities which claimed to maximize the 'sustainable yield' (i.e., MSY and corresponding mortality rate F_{MSY}), or maximize the yield per recruit (F_{max}). From an operational standpoint, it was recognized soon after that these underpinnings of the TAC could give undesirably high levels of fishing mortality and were ultimately rejected as appropriate criteria. Some studies actually demonstrated that exploitation of fish stocks at or near MSY could lead to collapse of the fish population. (For example, see Beddington 1979, Beddington and May 1977, May et al. 1979). Clark(1976) also showed that it is physically and economically impossible to achieve the theoretical instantaneous F_{max} level of fishing implied by the optimization techniques. For example, the optimal policy of fishing out particular year classes completely may require an infinite level of fishing effort. Accordingly, both MSY and F_{max} were ultimately rejected as appropriate operational criteria on which to establish global TACs.

Gulland (1968) first proposed the concept of $F_{0.1}$. In his argument for an understandable, generally applicable, and parsimonious criteria on which to base TACs, he arrived, quite arbitrarily, at the figure of 10% as a more conservative approach than 'maximizing' yield per recruit. In his analysis Gulland assumed that 'a marginal yield of 10% of the initial catch [i.e., of an unexploited stock] per unit effort is not worthwhile' (Gulland and Boerema 1973). (The notion of 'worthwhile' used here indirectly implies aggregate economic considerations related to the maximization of benefits.) Moreover, it was shown that $F_{0.1}$ is always less than F_{max} and hence provides a starting point to address possible overfishing problems associated with strictly maximizing the yield per recruit.

According to Anthony(1982), $F_{0.1}$ was introduced to ICNAF in 1972. Since 1975, when the practical difficulties surrounding F_{max} began to be acknowledged, more and more fish stocks came to be managed through TACs based on the more conservative $F_{0.1}$ fishing mortalities. Moreover, $F_{0.1}$ values have been a regular feature of assessments by

working groups of the International Council for the Exploration of the Sea (ICES) in recent years and they are presently the long-term objective level for fishing mortality for nearly all commercial fish stocks exploited internationally.

Calculation of $F_{0.1}$. Determination of the value of $F_{0.1}$ is provided by the yield theory of Beverton and Holt(1957). They modelled the exploitable resource stock as an age-structured or dynamic pool consisting of a number of different year classes or cohorts resulting from regular survival, birth and recruitment to the fishery. As the cohorts age, they grow while some die off due to natural causes (e.g., predators, disease, etc.). In Beverton and Holt's classical model applied to North Sea herring, uncertain information about the stock-recruitment relationship led them to consider recruitment each period to be a constant independent of the adult stock size. The problem then was to find the rate of fishing mortality on a given cohort in such a way that its full growth potential is realized.

Analysis of the yield (catch in weight) from each cohort is the primary concern of this approach. Beverton and Holt(1964) give closed form solutions for yields from a given cohort over its fishable life span as a function of the stock's following biological characteristics:

(1) The instantaneous rate of fishing mortality, F and natural mortality, M above some age, t_c, the age at recruitment to the fishery. Fishing mortality is assumed to possess what is known as 'knife-edge selectivity': all stock at or above the age of recruitment to the fishery, t_c are equally vulnerable to capture whereas all stock at ages below t_c are not susceptible to capture, i.e., $F = 0$ for the non-recruited stock. (For a discussion of fishing selectivity assumptions see also Walters 1986.)

(2) Growth (weight) and size (length) are describle by the von Bertalanffy growth equation at recruitment to the fishery. The weight-size relationship is assumed to be approximately cubic, i.e., if size (length) is described by $l_t = L_\infty[1 - e^{-K(t-t_0)}]$ then weight is $w_t = W_\infty[1-e^{-K(t-t_0)}]^3$ where K is the von Bertalanffy instantaneous growth rate at which the stock approaches its limiting size, L_∞, and weight, W_∞, and t_0 is the age at which stock units would have size and weight

zero if grown according to the same pattern for all its life (see also Gulland 1983, and Ricker 1975).

When the rates F and M are assumed to be constants independent of the cohort's age above t_c, and the growth curve is described by the von Bertalanffy growth curve, then the yield per recruit function, Y' is given by (1) (Beverton and Holt 1964). (For other derivations of (1) see also Ricker 1975 or Gulland 1983.)

$$(1) \qquad Y' = Y/(RW_\infty) = E(1-c)^m \sum_{n=0}^{3} \frac{U_n(1-c)^n}{1+n(1-E)/m}$$

where the elements of (1) are defined below:

U_n- summation variable with values +1,-3,+3,-1, for $n = 0, 1, 2, 3$ respectively, U_n dimensionless;

$E = F/(F+M)$, the harvesting exploitation rate, or the fraction of a year class which will be caught during its fished life span, $0 \leq E < 1$, E dimensionless;

$c = l_c/L_\infty \approx (w_c/W_\infty)^{1/3}$, average length per stock unit at age t_c of recruitment to the fishery, $l_c(w_c^{1/3})$ divided by the maximum attainable length of stock units, $L_\infty(W_\infty^{1/3})$; and $1-c$ is interpreted as the fraction of potential stock growth remaining after recruitment to the fishery, $1-c$ dimensionless;

$m = M/K$, the ratio of the instantaneous natural growth rate, M to the growth rate, K of the von Bertalanffy growth function, m dimensionless;

R = the count of stock units at recruitment age t_c, newly recruited to the fishery;

Y = the total catch or yield by weight for recruits entering the fishery at age t_c and growing at rate K, having mortality rate $F+M$ applied over their fishable life span;

W_∞ = the maximum attainable weight of a stock unit, $W_\infty \approx L_\infty^3$.

Thus, Y' is the total yield (by weight) per nominal recruit resulting from harvesting over the fishable life span a cohort of R recruits entering the fishery at age t_c, with average length l_c, and weight w_c and growing at a continuous rate K with natural mortality M and fishing mortality F as fraction of the maximum possible weight RW_∞ of the cohort (assuming continued survival of all members to their maximum attainable weight).

Moreover, as Clark(1976, p.272) notes, assuming F, M, t_c (or c) and annual recruitment, R remain constant then the stock is in a state of equilibrium, i.e., every year results in the same stock abundance and catch totals, and a second interpretation may be made about the value Y'. In this case, Y' denotes the annual yield by weight resulting from a fish population in equilibrium that consists of cohorts of stock units of all possible ages. This interpretation follows from the assumption of the stock in equilibrium. In equilibrium, the annual catch of stock units of a given age, e.g., $t_c + i$ must equal the catch of a single cohort during its ith year in the fishery. The total annual yield from all cohorts aged $t_c + i, i = 0, 1, 2, \ldots$ must equal then the total lifetime yield from a single cohort at all ages over its fishable life span.

From (1) total yield per recruit Y' is a function of parameters E, c, and m. The parameters E and c are control variables, i.e., the exploitation rate can be set by monitoring stock biomass and catch statistics, and the age (or size) at recruitment to the fishery can be set by fixing gear use, e.g., mesh size. Thus, the only endogenous biological variable required to determine yield in this model is m. The objective of the model then is to determine the appropriate combination of exploitation and recruitment timing to make the hypothetical yield as large as possible for the biology of a stock described by m. Table 1 provides a schedule of Y' values for $M = 0.20$ and $K = 0.15$ (corresponding to approximate parameters for northern cod stocks) and various E and c values. A worked example of the calculated values is also provided for illustration.

For given m, yields can be completely described by a yield isopleth diagram. Yield isopleth diagrams show the yield trade-offs between relative recruitment size, c and fishing mortality F (in place of E in (1)) to produce given levels of yield. Yield isopleths

are constructed by plotting F against c for given m to show curves of equal Y' values. Alternatively, yields for given m can be expressed as a function of F only by holding c constant, and *vice versa*. (For examples of yield curves see also Gulland 1983.) To illustrate, using the data from Table 1, Figure 1 present yield per nominal recruit curves for natural mortality rate, $m = 1.333$ and two values of relative length at recruitment $c = .3$ and $c = .6$.

For given values of m and c, the fishing mortality rate that maximizes yield per recruit is defined as F_{max}, where F_{max} is determined from the first order necessary conditions for maximizing F:

$$\left.\frac{\delta Y'}{\delta F}\right|_{F=F_{max}} = 0 \tag{2}$$

The fishing mortality rate for the $F_{0.1}$ criterion is defined formally for given values of m and c as

> the level of stock mortality due to fishing for which the marginal yield per recruit, $\delta Y'$ due to a small increase in fishing activity, δF is 10% of the marginal yield per recruit when the same stock is very lightly exploited, i.e., $F = 0$. (Gulland 1968, Deriso 1987)

In mathematical terminology,

$$\left.\frac{\delta Y'}{\delta F}\right|_{F=F_{0.1}} = 0.1\left.\frac{\delta Y'}{\delta F}\right|_{F=0} \tag{3}$$

In words, $F_{0.1}$ is the fishing mortality which equates to 0.1 (or 10%) of the slope of the yield per recruit function, Y' evaluated at the origin, or minimal fishing. The general form of the yield curve has a steep slope at the origin, i.e., the marginal increase in yield at low levels of fishing is large. However, at higher levels of fishing mortality the additional yield decreases. When the increase in fishing mortality finally results in an additional yield per recruit which is only 10% of that under minimal fishing, then we have reached the $F_{0.1}$ level. Graphical description of the yield curve and slope values provide further explanation of the derviation of $F_{0.1}$. Figure 1 shows $F_{0.1}$ for the values of m and c referred to in Table

1. Note that for all values of c, $F_{0.1}$ is conservatively less than F_{max}, the fishing mortality corresponding to the highest point on the Y' function.

In a recent paper Deriso(1987) has shown that there is a unique size of entry (determined by c) into the fishable population that maximizes yield under the $F_{0.1}$ fishing criterion. The fishing mortality corresponding to the appropriate age at entry is denoted as the 'optimal $F_{0.1}$' value and is characterized solely by the biological parameter $m = M/K$. Figure 2 presents Deriso's optimal $F_{0.1}$ values versus M for various values of K. For the values of the parameters for northern cod in Table 1 ($M = 0.20, K = 0.15$), the optimal $F_{0.1} = 0.23$ with $c = 0.60$. The instantaneous fishing mortality 0.23 corresponds to a annual total allowable catch of approximately 19% of the harvestable stock. (This percentage is called the annual exploitation fraction, and is denoted by, $h = E(1 - e^{-F-M}) = 0.19$.)

The classical description of the derviation the $F_{0.1}$ fishing mortality presumes that stocks are describable by a simple growth and survival process. However, in many cases the lack of appropriate information on stock growth behaviour, or radical departure of some stocks from the simple model representation make the application of the classical approach less intuitive. In many of these instances, such as the case of Atlantic scallops (Mohn *et al* 1987) a numerical approximation method is used to determine $F_{0.1}$. This method (based on a procedure first presented by Thompson and Bell 1934 and described in Ricker 1975) uses catch data to develop weight at age statistics. These statistics provide information about the shape of the yield per recruit function near the origin (i.e., with minimal fishing). The fishing mortality value is determined then by fitting the yield per recruit data to a curve with the desired slope (10% of its tangent at the origin) and iterating until $F_{0.1}$ is approximated to the desired level of accuracy.

Shortcomings of $F_{0.1}$. The original motivation for determining TACs based on a biologically determined fishing mortality rate was in response to the existing crises of depleting stocks and as a means of avoiding problems associated with the direct assignment of fleet allocations. (Although the problem of allocating shares of a global quota still remained.) The difficulties that arose in defining the appropriate reference point for TACs led to the arbitrary assignment of Gulland's '0.1' or '10%' rule as a conservative, biologically-based way of avoiding disasterously high fishing mortalities on vulnerable stocks.

Keeping in mind the difficulty with which commonly agreed reference points are arrived at in national and international forums, the establishment of $F_{0.1}$ as a generally accepted principle of fisheries management all over the world, marked a significant landmark for the preservation and effective management of commercial fisheries everywhere. However, as Munro(1977,p.39) stated, the model '...is gaining acceptance among biologists just at a time that it is losing favor with economists themselves.'

The Task Group on Newfoundland Inshore Fisheries (TGNIF, Canada 1987) comprised of distinguished researchers D.L. Alverson, F.W.H. Beamish, J. Gulland, P. Larkin, and J. Pope, recently examined $F_{0.1}$ regulation in an important study of Newfoundland cod stocks. They state,

> "$F_{0.1}$ has no particular biological virtue as the target for future policy, although thought to be relatively conservative if achieved. It had the practical advantage in the days of ICNAF, that it could be objectively determined from readily observable biological parameters (growth and mortality) and that it could be agreed upon as a target by countries with very different economic and social objectives. It also resulted in a value of F that was likely to be much closer to the value of F that would, in most cases, best fulfill social and economic objectives than that of other biological benchmarks, e.g., Maximum Sustainable Yield (MSY). However, if the size of the adult stock has a substantial influence on the magnitude of recruitment, *then the optimum F (and even the F giving MSY) might be below* $F_{0.1}$."

The issue of recruitment in determining fishing mortalities and yield estimates is fundamental. The interpretation of yield per recruit analyses as annual yields under equilibrium stock conditions must bear in mind the underlying assumption about constant

recruitment over time. Deriso (1987) compared the classical $F_{0.1}$ mortality (assuming as in the classical Beverton and Holt model, a constant recruitment relationship independent of the adult stock size) with mortality on stocks having recruitment *dependent* on the size of the reproducing stock. He showed that the $F_{0.1}$ value may actually exceed the MSY fishing mortality for the stock if its productivity rate is sufficiently low. Deriso used a Ricker stock-recruitment function to illustrate his findings. He obtained his results by comparing the values of F_{MSY} for the generalized Ricker curve with the value of $F_{0.1}$ for the same set of parameters. Comparing the two values, he showed that there exists a unique productivity factor for which $F_{0.1} = F_{MSY}$, otherwise $F_{0.1}$ is less than F_{MSY} (if the stock's productivity is relatively higher) or $F_{0.1}$ is greater than F_{MSY} (if the stock's productivity is relatively lower). In light of other work related to the dangers of MSY management, (for example, see Beddington 1979, Beddington and May 1977, May et al. 1979) this calls into question the original 'biological foundations' of $F_{0.1}$.

While claiming to rest on biological pretences, $F_{0.1}$ cannot claim more than an *ad hoc* economic underpinning. The argument that marginal yield from increasing effort should not fall below an arbitrary percentage is not consistent with the interplay of supply and demand, fluctuations in costs and prices, technological advances in fishing methods, and the decision making behaviour of individual fishermen which are all ignored in the determination of $F_{0.1}$. As Allen and McGlade(1987) state,

> "However, if there are criticisms to be made of the biological basis for fishery assessment, the economic calculations seem even less founded [...] Essentially, the economic calculation supposes not only the equilibrium state of the system, but also perfect information on the part of fishermen as the the possible 'return' on fishing effort of a particular kind [...] ...it denies the fact that action taken at one time will in fact influence the 'yield' at later times, and therefore that the relation between 'investment' and 'profit' not only has strong dynamic evolution, but also depends on what each of the actors chooses to do."

Clark(1976) recognizes the fact that the Beverton-Holt yield per recruit model is a static analysis and that their techniques are inadequate for determining dynamic factors such as the recovery of an overexploited stock. Moreover, the dynamic analysis of the Beverton-Holt model is much more difficult, the results are incomplete, and many questions

remain unanswered. For Allen and McGlade,

> "...the idea of calculating the 'yield per recruit' which is fundamental to [Beverton and Holt's] model, means that we study the average weight of catch which will be made from each young fish entering the system. Clearly, this only has a sense if the system is in a static, equilibrium state for at least the average life time of a fish, and this can be 8 or 12 years. In reality, fish populations, fishing effort, technology and even markets all change over such a time scale, and in addition, if the model is used to make management decisions, then these must also disturb the system and invalidate the model on which they are based."

Finally, among the most serious of all shortcomings of $F_{0.1}$ –and one that pervades *all* fisheries management–is the adequacy of substantive and reliable information and database systems on which to test, validate, and improve our understanding of the complex biological interdependencies of the resource systems being exploited. As Munro(1977) points out,

> "The real problem in setting the TACs will not be that of finding theoretically sound, but operationally useful, economic models, nor of obtaining relevant cost and price data (although admittedly the latter will be very difficult). Rather the real problem will be that of obtaining adequate biological models and data."

A problem particular to fisheries is that what is needed to understand complex resource systems is only partially observable at best. For example, even with modern technology, we admit to knowing very little about the reproductive performance and behaviour of scallops (Sinclair *et al* 1985); our understanding of cod migrations is at best vague (Canada 1987); and the list goes on. Recognition of the falliability of our estimations, projections, and information is the first step toward coping with this shortcoming.

Recent studies by Rivard and Foy(1987) and Brander(1987) on sources of errors in catch projections bring this issue to light. According to Rivard and Foy, improved forecasting of catch in the effective management of fisheries using $F_{0.1}$ must focus on reducing sources of error originating from

> "...the accuracy/variance of estimates of input variables, such as stock size, partial recruitment, and size of the recruiting cohorts, the stochastic nature of some input variables, such as natural mortality and mean weight-at-age, and external changes affecting input variables, such as changes in fishing patterns, in the gear type used, or in the time of year in which the fishery is prosecuted."

The biological, economic, and strategic shortcomings of $F_{0.1}$ are in part the consequence of a regulatory process built up by an historical tradition of reaction in the face of crisis situations. The result is a complex system of patchwork regulation reinforcing a 'we versus they' environment which ultimately leads to confrontation, mistrust and economic inefficiencies among the players in the game. The need is for a more refined understanding of the complex, dynamic process linking the players in the economic sector, e.g., fishermen and processors, with the biology of the fish stock (Allen and McGlade 1987, Silvert 1980, Huson et al 1984). The objective is to move away from 'reactive' management to 'proactive' management based on a clear understanding of behaviour among the players and a thorough analysis of the contingences of the changing, evolving system (Hilborn 1985, Wilen 1979, Lane 1988, 1989).

Fundamental to overcoming the problems associated with *any* regulatory concept is the need to articulate a long-term strategy with well-defined operational targets. This is best summed up by the authors of the TGNIF.

> "Ideally, management actions should flow from clear basic policies (e.g., "maximize the net economic returns from the fishery,") which can be expressed, following suitable analysis (e.g., of the costs and earnings under differing values of fishing effort,) as quantitative strategic targets of, for example, fishing mortality or spawning stock size, and then, given conditions in the current year, into tactical measures, e.g., the TAC for the following year. They should also take account of the uncertainties and associated risks that must exist in assessments of every fish stock. The group could find no record of such policy objectives by the federal government for the northern cod. The choice of $F_{0.1}$ seems to have been arbitrary, or a continuation of the ICNAF target without any examination of whether the target of an international body is necessarily appropriate for Canada with less need to command consensus.
>
> While the choice of a strategic target must be a political one, based on the desired balance of social and economic objectives, which will usually be partly conflicting, the choice is likely to be sound only if preceded by an analysis of the impacts of alternative strategies on the relevant characteristics of the fishery, e.g., on the costs and earnings, or the extent of employment."

Alternative approaches to $F_{0.1}$. The three most common approaches to managing fisheries can be described by the measure they seek to control. In general, control is exercised either on: (i) escapement, (ii) fishing mortality, or (iii) catch. Often fisheries regulation seeks to stabilize one of these variables. Figure 3 illustrates static harvest versus stock biomass for each of the three harvest policies referred to above. Our purpose is to investigate policies for establishing 'effective TACs' (i.e., those that lead to positive rent generation from harvesting, Munro 1977) based on a fishing mortality rate ((ii) above) as in the existing form of regulation for most commercially exploited Atlantic species. (Analysis and experience with the regulation policy approaches may be found elsewhere, e.g., see Walters(1986,1981), and Reed(1979), for the constant escapement policies used in the operational management of Pacific salmon.)

As previously discussed, the original focus of yield per recruit analysis on the biological objectives of the fishery led to the determination of theoretical fishing mortality rates F_{max} and F_{MSY} upon which the TAC could be based. While laudible criteria in themselves, they were found to be operationally infeasible and in some cases seriously damaging levels at which to regulate stocks. One problem is that these criteria are too narrowly focussed, emphasizing a single objective often at the expense of other reasonable objectives, e.g., socio-economic goals.

In reaction to the lack of attention on economic matters, an alternative is to focus the objective on economic performance. An appropriate goal is that of maximizing economic yield or MEY (Crutchfield 1975). Unfortunately, MEY shares the disadvantages of MSY in pursuing only one objective at the exclusion of all others. Moreover, without assuming catching rights to competitive fishing interests, e.g., enterprise allocations, or individual transferable quotas (ITQs), this approach is doomed to investment spiralling and economic inefficiency, including rent dissipation.

Some researchers (Roedel 1975, Keeney 1977) suggested a fixed multiple criteria optimization as a means of circumventing the problems associated with the narrow single

objective approach. While this recognizes a serious fault with other approaches, the theory of multiple criteria decisions making does not address the issue of how the various and often conflicting goals are to weighted properly or pratically applied.

The alternative of satisficing (Simon 1957) is presented as a means for setting strict feasible bounds on the key performance measures of the fishery, e.g., stock assessment, catch per unit effort, total catch. The bounds or goals recognize the inherent uncertainty of the system while at the same time allowing some degree of 'probing' and experimentation in the design of strategies for regulation (Walters 1986). Moreover, the bounds could be set to achieve some relative degree of stability in the system with regard to the stock and the economic indicators. The level of operations will provide feedback and an enhanced information state with which to develop new bounds and strategies for future periods.

Alternatives to $F_{0.1}$ can be stipulated in terms of a different fishing mortality reference point for arriving at effective TACs. The value of a 'more appropriate' F must be dynamic, (Munro 1977) i.e., changing over time in response to changes in the actual system. Moreover, it is intuitive that any valid alternative F will be bounded above by F_{max}. In the following section, the framework for a model used in the analysis of biological (stock) and economic indicators is described as a means of evaluating fishing mortality regulation and for determining effective TACs.

A Model Framework

Model Components. The construction of models which link dynamic fish populations to the economic performance of the related fishery have been discussed widely. Clark(1976,1985) presents the foundations of bioeconomic modelling in fisheries. Using the techniques of applied mathematics and economic theory he constructs normative hypotheses for the management and control of fisheries resources. Silvert(1980) presents a general framework for the development of linked models which include emphasis on the

primary and secondary producers in the fishery and their interaction with the resource stock. More recently, Schnute(1985) presents a general theory for the analysis of catch and effort data based on the dynamic pool model developed previously by Deriso(1980). In this paper Schnute stops short of making links to the economic side of the fishery sector, his intent being that of discovering more about the partially observable stock through actually observed catch and effort empirical data. Walters(1986) elaborates on the concept of adaptive management as a means of learning about and extracting from partially observable and stochastically varying resource stocks in efficient ways.

This section describes the major components for the development of a bioeconomic model directed toward the evaluation of various fishing mortality schemes as reference points for setting TACs for individual commercial species. The model must include the key elements which make up the system under study. This includes the stock and its natural growth behavior; the harvesting sector, i.e., the commercial fishermen, and their behavior with regard to effort and investment decisions; and the regulators and their behavior with regard to managing the fishery. As well, the interaction of the behaviors of the stock and the fishing sector under the existing regulatory rules provides the key to the dynamic evolution of the system. (See Figure 4.)

Taking the interacting elements of the system into account, the major components of the model under a proposed fishing mortality regulation scheme are identified as:

1. Stock Mortality, Growth and Recruitment.
2. Decision Making Behaviour of Fishermen.
3. Economic Performance Measures.

The composition and details of these components of the bioeconomic model are discussed below. The model is illustrated using aggregate stock equilibrium estimates broadly based on the Newfoundland nearshore cod fishery in (NAFO zones 3KL). Details on model development including parameter values used to produce the sample results provided in Figures 6 and 8 through 10 are given in Appendix B.

1. Stock Mortality, Growth and Recruitment. In general, the dynamics of stock growth depend on the regulated exploitation rate and on the biological growth properties of the stock. These include information about:

1) the rate of natural survival (i.e., in the absence of fishing) of the stock over time, or its complement, the rate of natural mortality;
2) the rate of growth of the stock by weight and length;
3) the stock-recruitment relationship defining the renewal characteristics of the population from season to season.

A simple descriptive view of the dynamically changing stock biomass can be developed by combining aspects of stock growth with the fishing mortality strategy of regulation. As an illustration, consider the example presented in Figure 5 to describe the dynamics of aggregate stock growth (i.e., all ages together) from season to season. Beginning with an initial stock biomass, S, recruitment occurs prior to the opening of the fishing season (quadrant I). Next, the stock is harvested up to the regulated fishing mortality, F (quadrant II). The stock is divided into catch and escapement (quadrant III) before the effects of natural mortality (quadrant IV) result in a new initial stock for the next season, and so on. While simplistic in nature, this graphical model of stock growth shows the expected impact of the stock-recruitment relationship and the fishing mortality regulation on the changing size of the stock. This view does not reveal the significant effects of fluctuations in mortality, stock recruitment, and growth on the evolving size of the biomass.

The yield per recruit analysis of Beverton and Holt also focuses on these biological growth aspects of the resource system. The classical dynamic pool models permit analysis of the stock by age. They assumed constant mortality across all ages of the population, recruitment to the fishery at a specific age, deterministic length and weight at a given age, and constant recruitment independent of the size of the adult stock.

Deriso(1980) generalized the surplus-production function approach to population growth (e.g., Schaefer logistic curve) with the dynamic pool, age-structured approach which included provision for a size dependent stock-recruitment relationship. In spite of its two simplifying assumptions of (i) knife-edge recruitment, and (ii) constant mortality (independent of age), this model has been hailed as a fresh approach to modelling resource population dynamics with an intuitive slant (Walters 1980). The Deriso model has been used elsewhere to describe population growth (Schnute 1985) and is the most flexible procedure for use in a model of the type described in this paper.

The Deriso model implicitly uses Ford's model of fish growth. Schnute(1985) generalizes these parameters to other growth models including Brody's growth model, and von Bertalanffy growth. This is useful is linking the assumptions of the yield per recruit theory and the determination of $F_{0.1}$ with the stock dynamics model. Gulland(1983) provides the connection between stock growth by weight and by length in the various growth models.

Finally, Schnute(1985) provides a general description for stock-recruitment relationships by a set of parsimonious parameters for growth, optimality and functionality, including the description of a wide variety of well-known functions such as the Schaefer, Ricker, and Beverton and Holt stock-recruitment functions.

Figure 6 presents illustrations of model results using Deriso's and Schnute's approaches to describe the impact of alternative fishing mortality schemes on the stock at equilibrium under the regulation. Of notice is the fact that as F increases, biomass, age, length, and weight all fall as a consequence of fewer fish being around at equilibrium.

2. Decision Making Behaviour of Fishermen. Fishermen tend to make decisions based on their own personal attitudes and on their perceptions and experiences gained in the fishery. Among other signals, important observations about the state of the fishery are learned from catch results. Catches, or yields provide feedback to the fishermen about the current and anticipated status of the fishery. Moreover, this information is the basis

for concrete decisions with regard to expanding fishing operations or possibly switching to other sources of income.

To illustrate, consider the events characterized by the graphs of Figure 7. In a competitive fishery, fishermen move to capture a share of the total catch which is regulated (e.g., through $F_{0.1}$) as an exploitation fraction, h (quadrant I). As a conseqence of a share of this TAC, each fisherman, depending on costs effectiveness, capitalization, extent of effort over the season, etc., receives a seasonal landed value income as a direct function of the catch and the price of the catch (quadrant II). This information provides the necessary feedback to the fisherman for deciding about funding reinvestment into the fishery for next season, buying new capital equipment (e.g., boat engines, gear, etc.,), or selling off capital (quadrant III - additions to and deletions of current capital). The resulting capitalization of the fleet in the next season coupled with the regulated fishing mortality establish the time required for the fleet to capture the TAC, i.e., the length of the season (quadrant IV). This framework provides a basis for examining the dynamic interaction between decisions made by fishermen effecting the evolution of the fleet and regulation policy.

In modelling the decision making behavior of fishermen, two primary decisions may be considered: (1) intraseasonal decisions and (2) interseasonal decisions. First, fishermen make decisions at various periods throughout each fishing season about where and when to fish. These planned fishing effort decisions are denoted as intraseasonal decisions. The decisions made by the collective group of fishermen determine fleet dynamics in a spatial fishery as well as the distribution of fishing effort and landings by the fleet over the season.

Second, fishermen make regular decisions to investment (or disinvest) in the fishery. These investments, assumed to occur between each season, are denoted as fishermen's interseasonal decisions. They include decisions about upgrading existing capital or switching to other types of capital (including other fisheries). The capital structure of a fishing enterprise defines its fishing power relative to other enterprises in the fleet and is a discriminating factor in determining the income earning potential of comparable enterprises.

Moreover, the income of an enterprise is linked to investment potential in future periods.

Modelling decision making behaviour may be done by considering the fleet as an aggregate group. In aggregate models, all individual decision making units are considered to act in an 'average' way. While this approach simplifies analysis, it often hides the variability and structural evolution inherent in the real system. A more realistic approach is to consider the decision making of individual units directly. Models for individual decision making have been developed and tested by Lane (1988,1989). Hilborn and Walters (1987) present a simulation system for modelling stock and harvesting interactions including fleet dynamics and decision making. These models provide a framework for modelling fishermen decision making in the context of the resource system being managed.

Figure 8a displays a simple effort feedback model of fishermen reacting to current levels of profit in the fishery, i.e., the higher the current profit, the more effort fishermen are willing to invest in the future in anticipation of continued profits in the fishery. Figure 8b illustrates the increasing effort required to capture higher and higher exploitation rates on the stock in equilibrium. Note that the effort needed to exploit more of the stock increases at a faster rate in this example than the corresponding increase in stable yield.

In Figure 9, two views of the impact of the regulated fishing mortality rate, F are expressed relative to the seasonal fishing effort. Fishing effort and catchability determine the ability of the fleet to capture the TAC. Note that as the equilibrium stock level increases, the longer the season length needed to catch the specified exploitation fraction, h. Similarly, for a given equilibrium stock size, if there is more capital in the fishery, the length of the fishing season must decrease.

3. Economic Performance Measures. The economic performance of the proposed model links the biological dynamics of the stock with the decision making dynamics of fishermen. This component of the model includes the explicit relationships between catchability ('fishing power') and stock size, catchability and capitalization, catch and profit,

season length (relative to the TAC and catchability), landed value and costs of fishing effort.

Feedback is provided from the output of the economic measures to decision making, e.g., effort planning and investment for future periods based on observed results to date. The implications on catchability combined with the current regulation in effect influence the size of the stock which in turn impacts economic performance and decision making in future periods.

Figure 10 illustrates examples of the economic evaluation of regulated fishing mortality alternatives. Figure 10a displays the average profit position of the fishermen for various F values at equilibrium levels of effort, stock, and real costs and prices. In considering the economic position of the fishing sector, this type of result is pivotal to the evaluation of the fishing mortality value which should be used as a basis for calculating the current TAC for the species. Figure 10b displays the movement toward profit stability, *ceteris paribus* when the stock biomass has an initial value away from its stable equilibrium level and the stock is regulated with a fixed fishing mortality over time.

Conclusions and Extensions

Current regulation of commercial fisheries using the $F_{0.1}$ criterion to establish seasonal global TACs is coming under increasing criticism. The *ad hoc* nature of Gulland's 10% rule, while having some desirable characteristics, e.g., conservative estimation always less than F_{max}, may not be applicable across all fisheries. In particular, the stock-recruitment relationship and the economic underpinnings of the level of fishing mortality must be considered explicitly in determining the TAC in order to ensure the continued viability of commercial fisheries.

The biological *and* economic impacts of examining alternative criteria for establishing

the TAC using the fishing mortality regulation scheme can be examined by developing appropriate strategic models on a species by species basis. Such models can be used to evaluate fishing mortality regulation in general, and alternatives to $F_{0.1}$ in particular, by providing a projection of explicit biological and economic criteria for the determination of "good" fisheries management strategies. The accuracy of model projections for a fishery of interest will depend on the reliability of the data, and the understanding of the interacting components of the system. In any case, the modelling procedure will enlighten the decision maker to the strong interdependence of the various biological and economic elements of the fishery.

The important stochastic nature of fisheries systems including variability in recruitment, prices and costs from season to season make this system difficult to control and stabilize. Recognizing that fisheries are inherently stochastic is the first step toward developing policies which exploit this variability over time. Lessons from the exciting area of adaptive control encourage this idea. Moreover, dynamic analysis of models which incorporate adaptive policies will lead to greater flexibility in regulation and ultimately a more valuable and thriving fisheries sector.

Application of the proposed model is currently underway on two fronts: (1) the Newfoundland northern cod fishery, and (2) the Georges' Bank scallop fishery.

The Newfoundland Cod Fishery. The original motivation of the current analysis was fuelled by the work of the Task Group on the Newfoundland Inshore Fishery and their analysis of disappearing inshore cod stocks relative to the historical $F_{0.1}$ management strategy. In the application of the model to the Newfoundland cod fishery, we seek to understand the real impacts of past regulation as well as to examine the expected trend in future stock and economic impacts under alternative fishing mortality levels. Other areas of interest in this application include the evolution of the inshore and nearshore fishing fleets, and the impact on the stock due to significant harvesting by foreign fishing fleets in the nose and tail of the Grand Banks.

The Georges' Bank Scallop Fishery. This fishery is also currently managed under $F_{0.1}$ but, unlike the cod fishery, the scallop fishery is localized to specific spatial zones. As well, this offshore fishery is primarily a dedicated and restricted access operation. Vessels are managed through enterprise allocations with dragging rights restricted to a limited numbers of vessels held by large fishing enterprises. Alternative levels of fishing mortality will be evaluated along with the operation of the enterprise allocation system.

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Appendix A

Terms of Reference

Economics of $F_{0.1}$

Purpose: To assess the economic impact of alternatives to $F_{0.1}$ resource management. The assessment should be undertaken by examining the impact of different levels of fishing effort on a given stock of fish. A major part of this work will include measuring the impact of the resultant fishing mortality on the economic performance of the harvesting and processing sectors. Key impact areas to examine include:

1) the impact on the biomass

2) the impact of catch rate change

3) the impact of change in quality and size of fish

Appendix B
Details of Model Development

This appendix presents details for the illustration of a proposed model framework for the bioeconomic evaluation of TACs based on prescribed fishing mortalities. In particular, the derivation of Figures 6 and 8 through 10 which appear in the text is described. Data for the development of these figures are based on empirical data for northern cod stocks and, more specifically, for the 3KL nearshore fishery.

1. Stock Mortality, Growth and Recruitment. Deriso's model is used as the fundamental model for stock dynamics. There are two sources of stock mortality: natural mortality, M (assumed to be the rate applicable to all age classes of the stock), and fishing mortality, F ('knife-edge' fishing mortality assumed beyond recruitment age, t_c). Stock growth (by weight and size) is according to the von Bertalanffy growth model. Recruitment to the fishery is expressed in the general form as described in Schnute(1985).

Stock dynamics (by weight) are described as:

$$(A.1) \qquad N^*_{t+1} = (1-h_t)s_t N^*_t + V_{t+1}R_{t+1} + \rho(1-h_t)s_t[N^*_t - (1-h_{t-1})s_{t-1}N^*_{t-1}]$$

with

- $N^*_t = \sum_{a=t_c}^{t_\infty} w_{at}N_{at}$ - the total harvestable biomass (i.e., all cohorts ages $a = t_c$ or greater), w_{at} is the average weight of stock units at age a, and N_{at} is the number of stock units (pieces) at age a in period (year) t;

- the growth by weight of each stock unit is defined by two parameters V_t and ρ where V_t is the weight of a stock unit born in period $t - t_c$ at recruitment age t_c and, ρ is the period over period Ford-Brody growth parameter related to the von Bertalanffy growth coefficient K, i.e., $K = -\log \rho$;

- natural and fishing mortality are assumed to occur together, so that the natural survival rate, s and the exploitation fraction, h in each period t (assuming $F_t = F$, and $M_t = M$) are given by $s = \frac{M+F}{Me^{M+F}+F}$ and $h = \frac{F}{M+F}(1 - e^{-M-F})$;

- stock-recruitment is described by the productivity of the stock, α, the carrying capacity of the stock, β, and the functionality of the stock-recruitment relationship, γ. Define the recruited population (in number of pieces) at time t, R_t as:

  $$R_t = \alpha N^*_{t-t_c}(1 - \beta\gamma N^*_{t-t_c})^{1/\gamma} \tag{A.2}$$

  where it is implicitly assumed that recruitment occurs in each period just prior to stock reduction by natural or fishing mortality.

Equilibrium stock levels for various F are obtained by setting $N^*_t = N^*$ for all t in (A.1) and (A.2). Estimates of parameter values for northern cod are given in Ricker(1975) and Canada(1984). These are: $M = 0.20, K = 0.15, V = 1$ kg at age $t_c = 4$ years. Recruitment is modelled using the Beverton-Holt stock-recruitment relationship with scaled parameter values: $\alpha = 5, \beta = 0.02$, and $\gamma = -1$. Equilibrium stock level indices N^* and N for these parameters and for various F are provided in Figure 6a.

Statistics on the equilibrium stock resulting from continued application of a fixed F may be determined directly. Sample statistics are recorded in Figure 6b and include: (i) average age above recruitment per stock unit captured; (ii) average weight per unit stock captured; (iii) average length per unit stock captured relative to the maximum unit stock size; and (iv) total recruits weight per total harvestable biomass. The expressions for (i)–(iv) are as follows:

(i) Average Age:

$$\bar{a} - t_c = \frac{(1-h)s}{1-(1-h)s}\{1 - [(1-h)s]^{t_\infty - t_c} - t_\infty[(1-h)s]^{t_\infty - t_c + 1} \tag{A.3}$$

where t_∞ for northern cod is estimated at 20 years.

(ii) Average Weight:

$$\bar{w} = N^*/N \tag{A.4}$$

(iii) Average Length:

$$l_{\bar{a}}/L_\infty = 1 - e^{-K\bar{a}} \tag{A.5}$$

(iv) Recruits per Biomass (RPB):

$$\text{RPB} = VR/N^* \tag{A.6}$$

2. Decision Making Behaviour. Fishermen's decisions concerning planned effort for the upcoming season are based on the observed economic rewards of previous seasons. Effort for the upcoming season may be described as a function of previous net income, bounded below by a minimum time (e.g., related to the time required to maintain unemployment insurance in the off season), and bounded above by the maximum length of the fishing season (related to the capital structure of fishing enterprises including the age, length of vessels, etc.,). One such model for planned fishing effort is

$$E_{t+1} = E_{max}/(1 + \frac{E_{max} - E_0}{E_0} e^{-r\pi_t}) \tag{A.7}$$

where E_{max} denotes the maximum season length (in standard days fished), E_0 is the minimum season length, r is the instantaneous rate of growth of effort per unit change in the previous season's profit, π_t. Data from the 3KL nearshore cod fishery (Canada 1984) suggest the following values for the parameters: $E_{max} = 175$ days, $E_0 = 30$ days, $r = 0.03$. Figure 8a presents the graph of planned effort, E_{t+1} versus π_t for various r values.

The annual harvest or yield by weight, Y^* for the stock in equilibrium under fishing mortality F is:

$$Y^* = hN^* \tag{A.8}$$

Figure 8b presents a plot of Y^* versus F.

The actual catch by fishing enterprises is related to fishing capital, C_t the planned effort, E_t and the harvestable stock, N_t. Fishermen make investments and effort decisions presumably to improve their own catch potential, *ceteris paribus*. Define the catchability of the fleet as the catch in pieces during a standard day of fishing effort. Let λ_t denote the catch (in pieces) per standard day fishing, with

$$\lambda_t = A(N_t)^{a_1}(K_t)^{a_2},\ a_1 + a_2 < 1, A, a_1, a_2 \geq 0 \tag{A.9}$$

where A is a proportionality factor, and a_1, a_2 are scale factors for capital and stock respectively. The catch in pieces is then given by $\lambda_t E_t$.

However, for given fishing mortality, F and fixed C and N, the catchability λ (assuming A, a_1, a_2 are known) is fixed. Accordingly, the required effort E is found by

$$E = hN/\lambda \tag{A.10}$$

Figure 8b presents a graph of effort required versus F for capital, C indexed at 100 and catchability parameters $A = 0.125, a_1 = 0.3$ and $a_2 = 0.2$.

The length of the harvesting season may be similarly described by determining the effort E required to capture the target fishing mortality rate F for the stock in equilibrium as a function of capital C, and stock abundance N. Using $(A.9)$ and $(A.10)$ then

$$E(N, C) = \frac{hN^{1-a_1}}{AC^{a_2}} \tag{A.11}$$

Figure 9 presents graphs of 'season length', E required to capture the TAC (in terms of h) as a function of different C and N values. Data values are $A = 0.125, a_1 = a_2 = 0.25$. Figure 9a sets the capital index at $C = 100$ for stock abundance indices between 100 and 1300. Figure 9b fixes the stock index at $N = 700$ for capital indices between 50 and 150.

3. Economic Performance Measures. Annual economic performance of the fishery may be measured by total landed value (revenues), total operating cost, and total net

operating income (before taxes). The landed value of the fleet depends on the exogenously set price per unit weight, $p_t = p$, the TAC, and on the planned effort of the fleet. If the TAC is restricting, then planned effort must be curtailled; conversely, the TAC may not be captured if planned effort is below that required to capture it. Thus, the landed value in period t, LV_t is

$$LV_t = p\lambda_t E_t \tag{A.12}$$

The cost of fishing operations is comprised of four components. Total operating costs include: (i) fixed costs (licencing, insurance, fees), (ii) variable costs related to effort (fuel, food, wharfage, and bait), (iii) repair and maintenance (gear and maintenance), and (iv) labour (crew and skipper wages determined as a share of the total landed value of the catch). Total operating costs in period t, TC_t may be written as

$$TC_t = c_0 + c_1 C_t + c_2 E_t + c_3 LV_t \tag{A.13}$$

where c_0 is fixed cost, c_1 is the cost of repair and maintenance per unit of capital, C_t, c_2 is the cost per standard day fishing, and c_3 is the proportion of total landed value going to the skipper and crew for labour. For the 3KL nearshore northern cod fishery estimated nominal parameter values in 1982 dollars are (Canada 1984): $p = \$0.37/\text{kg}$, $c_0 = 10$, $c_1 = 0.07, c_2 = 0.10, c_3 = 0.60$.

The annual net operating income from fishing (before taxes) is

$$\pi_t = LV_t - TC_t \tag{A.14}$$

Figure 10a presents landed value, operating cost, and net operating income (before taxes) using the above parameters for the stock in equilibrium under various fishing mortality rates.

Finally, Figure 10b presents the evolution of the equilibrium net income position of the harvesting sector when the stock abundance is initially in a state which is not in equilibrium. The figure shows how the income position adjusts as the stock moves in response

to a fixed fishing mortality rate $F = F_{0.1} = 0.23$. The dynamics of this deterministic pattern include the possibility of investment, disinvestment and real depreciation of capital in the harvesting sector. Investment decisions are assumed to be a direct function of the current profit level. New investments occurring at the end of period t and available for the next season are assumed to be $100k\%$ of the net operating income in period t, π_t. After accounting for real depreciation of the existing capital at a fixed rate ν per season, then the new capital value at the beginning of period $t+1$ is

$$C_{t+1} = (1-\nu)C_t + k\pi_t \tag{A.15}$$

Empirical evidence of this model for capital investment in fisheries have been investigated by Lane(1985) for the case of Pacific salmon trollers.

Exploitation Rate E†	*Fishing Mortality* F‡	*Yield per Nominal Recruit* $c = 0.3$	$c = 0.6$
0.05	0.01	.015714	.009580
0.10	0.02	.030783	.018918
0.15	0.04	.045171	.027998
0.20	0.05	.058843	.036801
0.25	0.07	.071763	.045309
0.30	0.09	.083892	.053501
0.35	0.11	.095193	.061354
0.40	0.13	.105632	.068846
0.45	0.16	.115174	.075950
0.50	0.20	.123793	.082640
0.55	0.24	.131468	.088887
0.60	0.30	.138192	.094663
0.65	0.37	.143974	.099938
0.70	0.47	.148851	.104685
0.75	0.60	.152897	.108878
0.80	0.80	.156237	.112499
0.85	1.13	.159070	.115539
0.90	1.80	.161687	.118008
0.95	3.80	.164487	.119943

†Exploitation rate fraction due to fishing mortality, $E = F/(F + M)$.
‡Instantaneous rate of harvesting, $F = ME/(1 - E)$.

Table 1. Yield per nominal recruit values for approximate Northern cod parameter values: $M = 0.20, K = 0.15,\ m = M/K = 1.333$. Example calculation for $E = 0.5, c = 0.3$ using equation (1):

$$Y' = .5(1-.3)^{1.333}\left[1 + \frac{-3(1-.3)}{1+\frac{(1-.5)}{1.333}} + \frac{+3(1-.3)^2}{1+\frac{2(1-.5)}{1.333}} + \frac{-1(1-.3)^3}{1+\frac{3(1-.5)}{1.333}}\right] = 0.123793$$

Yield Per Nominal Recruit vs F
M/K=m=1.333

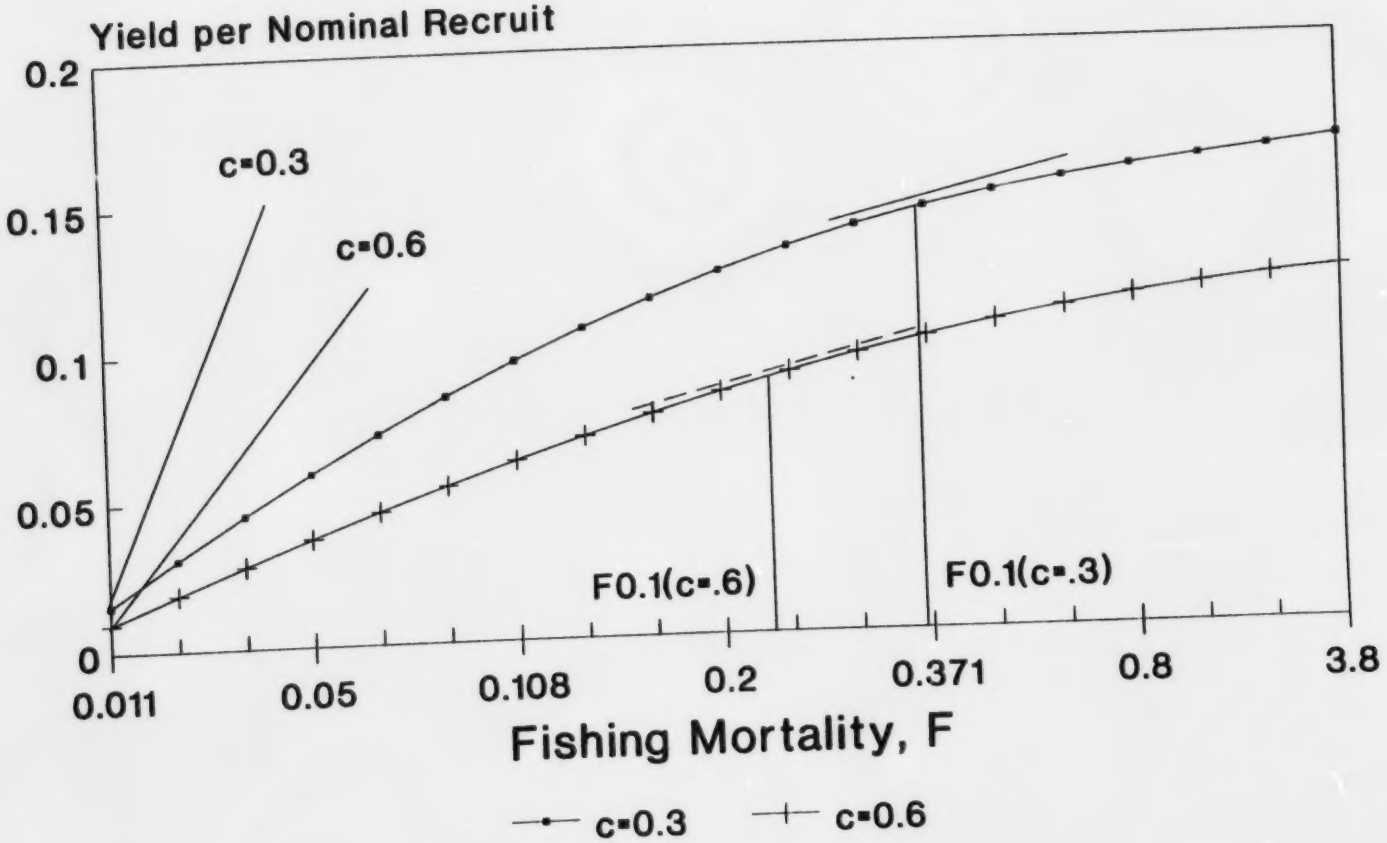

Figure 1

Deriso's Optimal F0.1
for various K and M

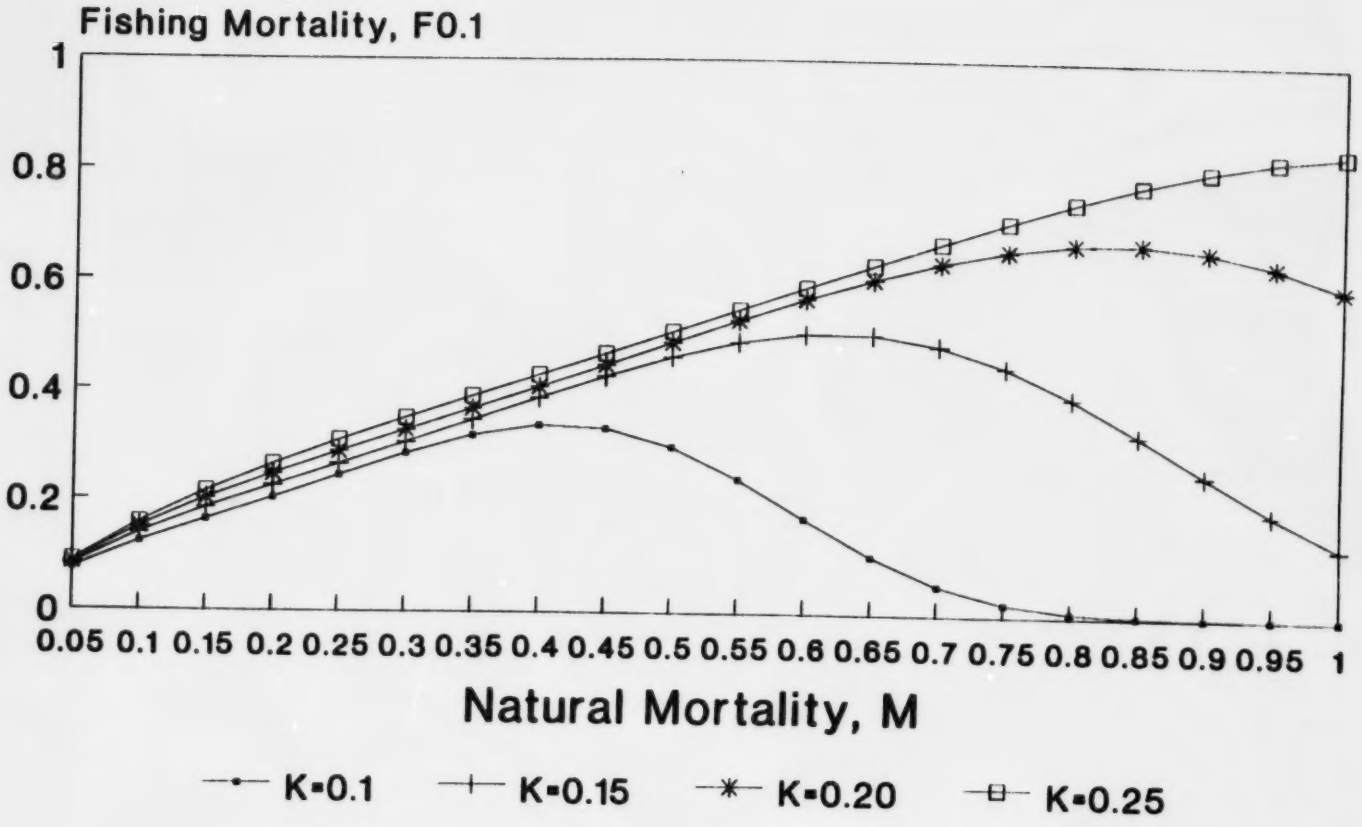

Figure 2. K is von Betalanffy growth.

Harvest Policies versus Biomass

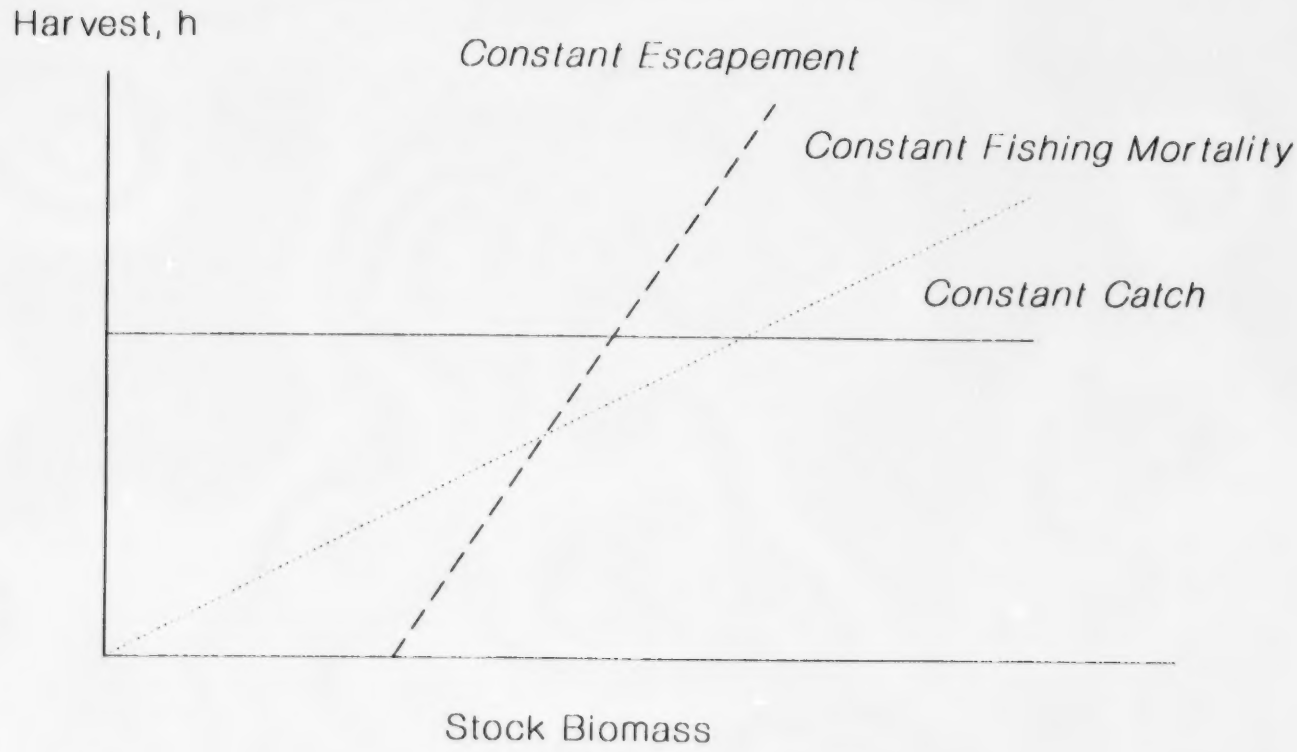

Figure 3

Resource Interaction Model Dynamics

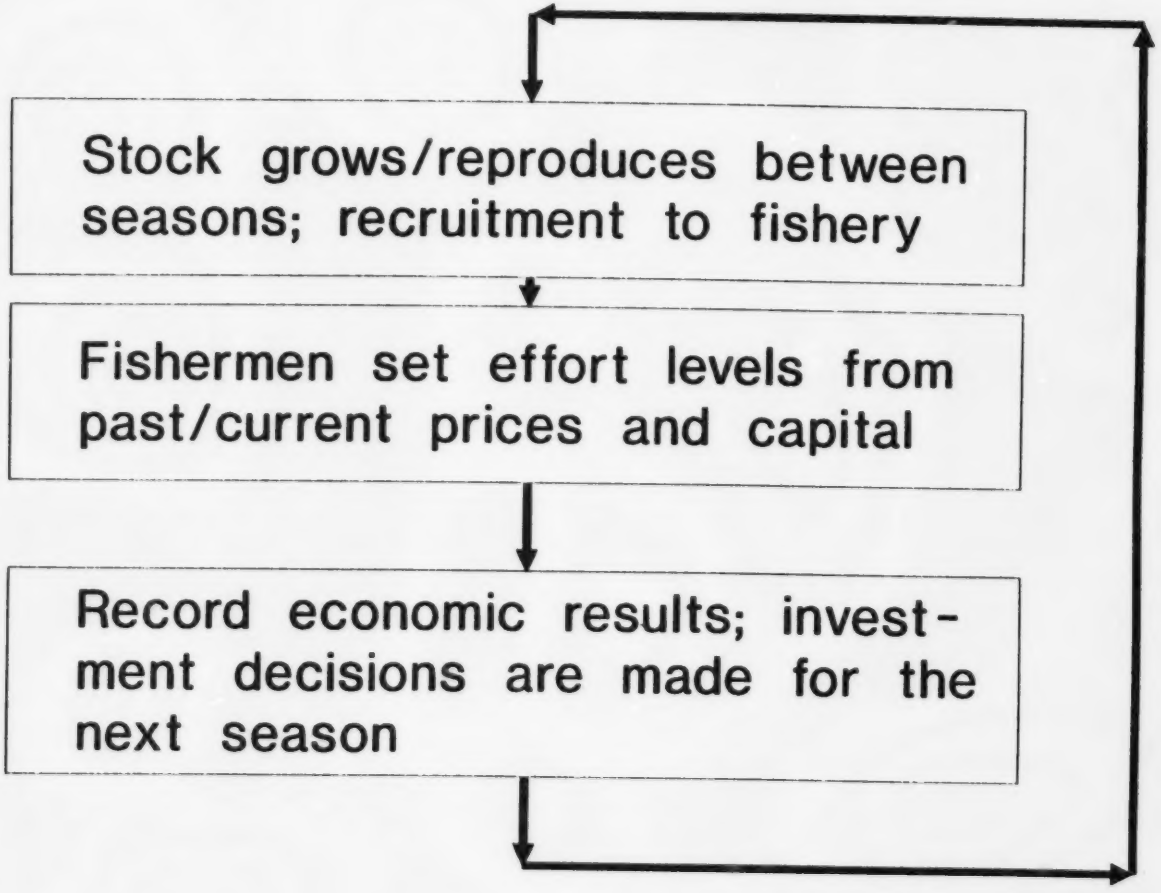
Stock grows/reproduces between seasons; recruitment to fishery
Fishermen set effort levels from past/current prices and capital
Record economic results; investment decisions are made for the next season

Figure 4

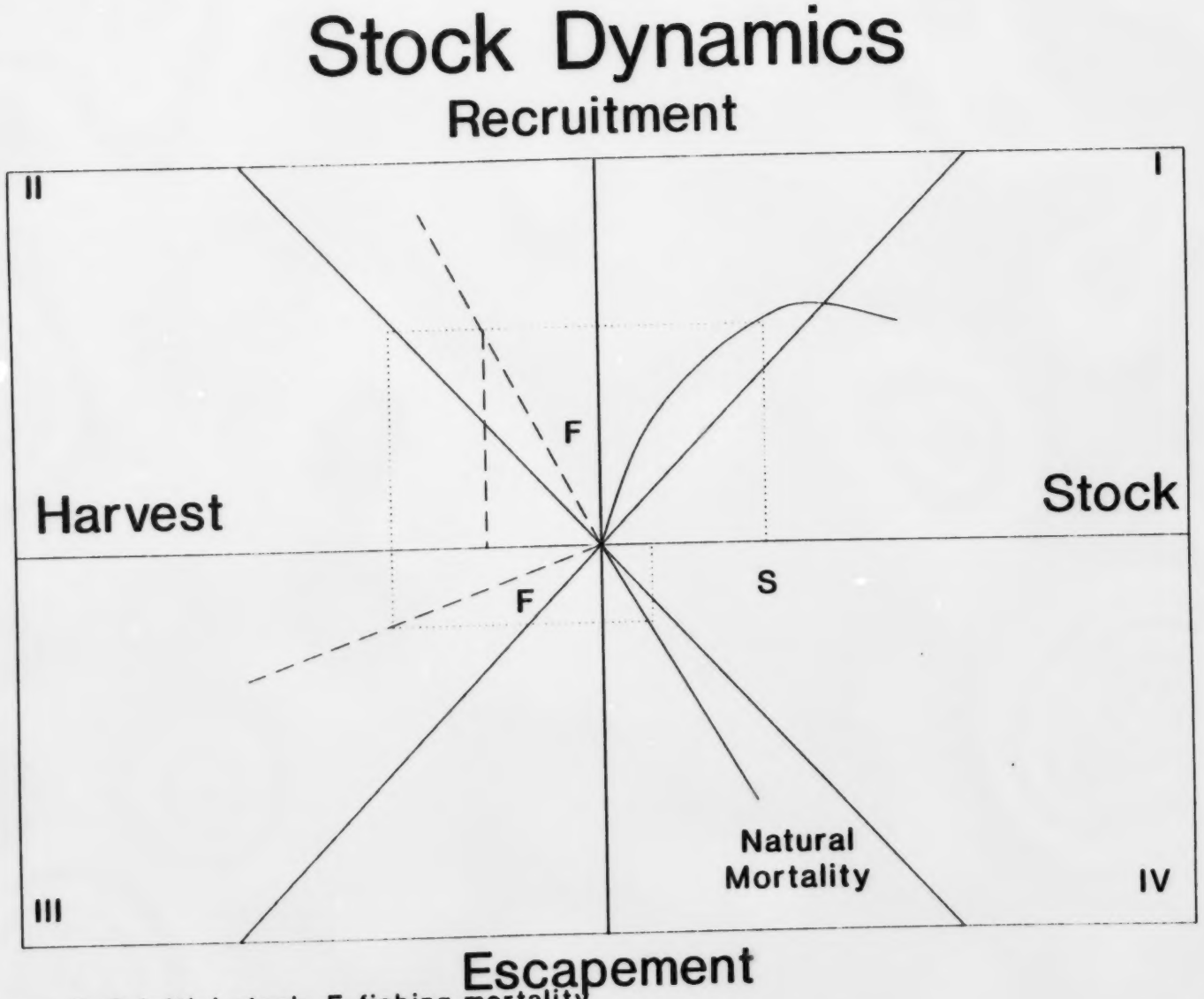

Figure 5. S-initial stock; F-fishing mortality

Equilibrium Harvestable Stock versus F

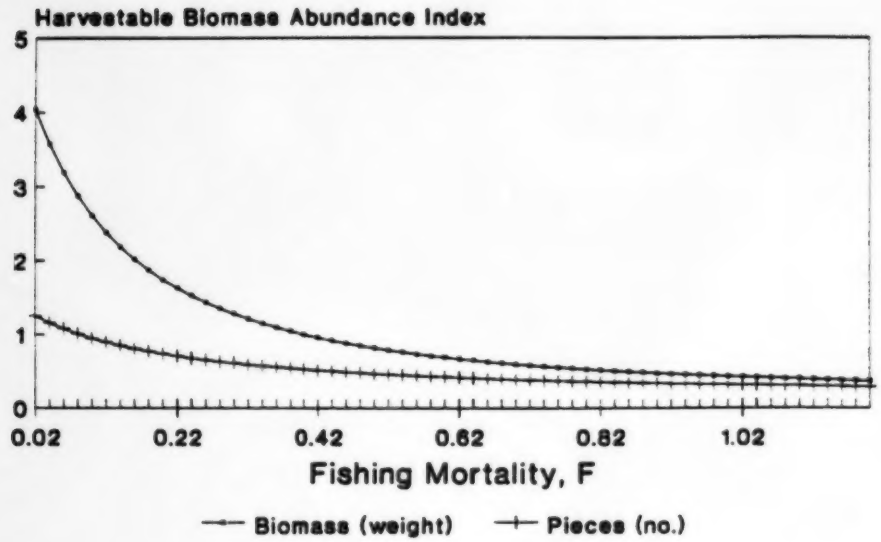

Figure 6a

Equilibrium Stock Statistics versus F

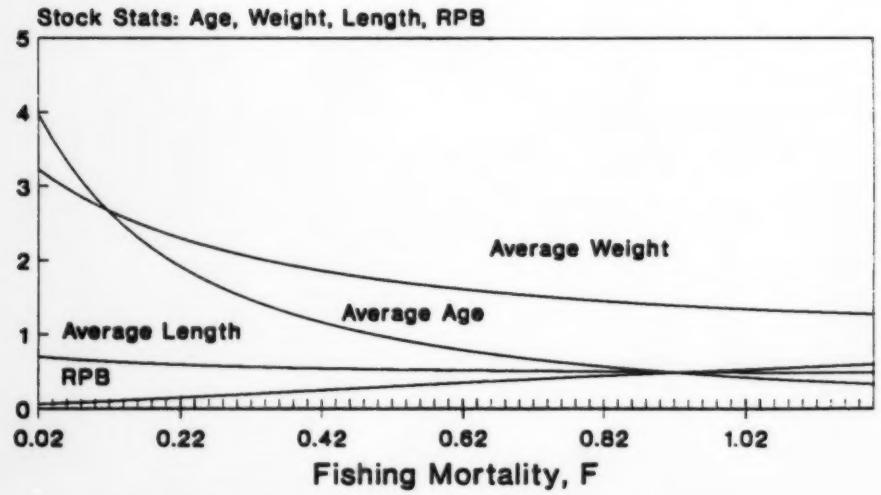

Figure 6b. Age-ave age of catch above recruitment; Weight-ave per stock unit captured (kg); Length-ave per unit stock captured relative to max; RPB-recruits weight per total biomass.

Fishing Sector Dynamics

Harvest/Season Length

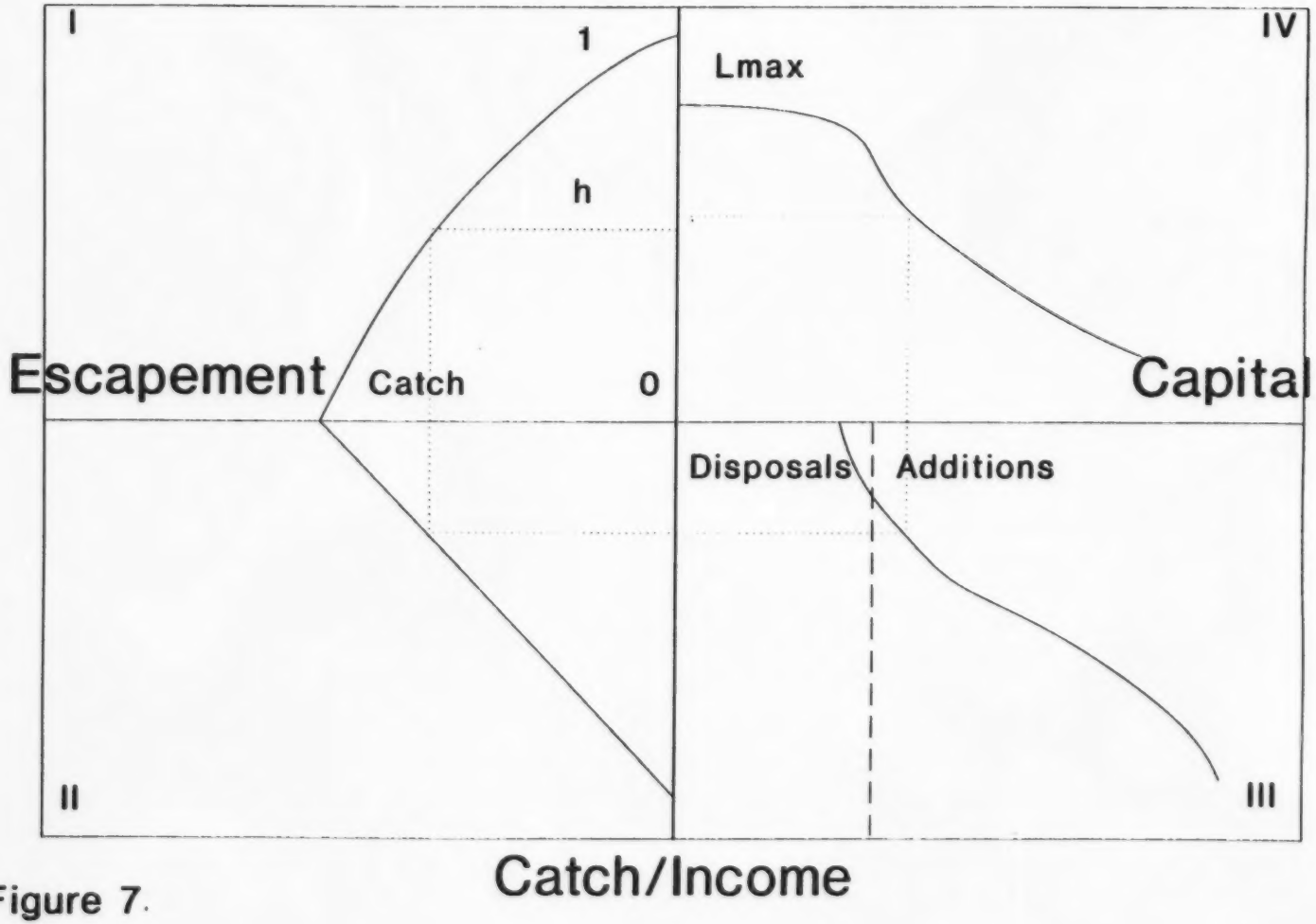

Figure 7.

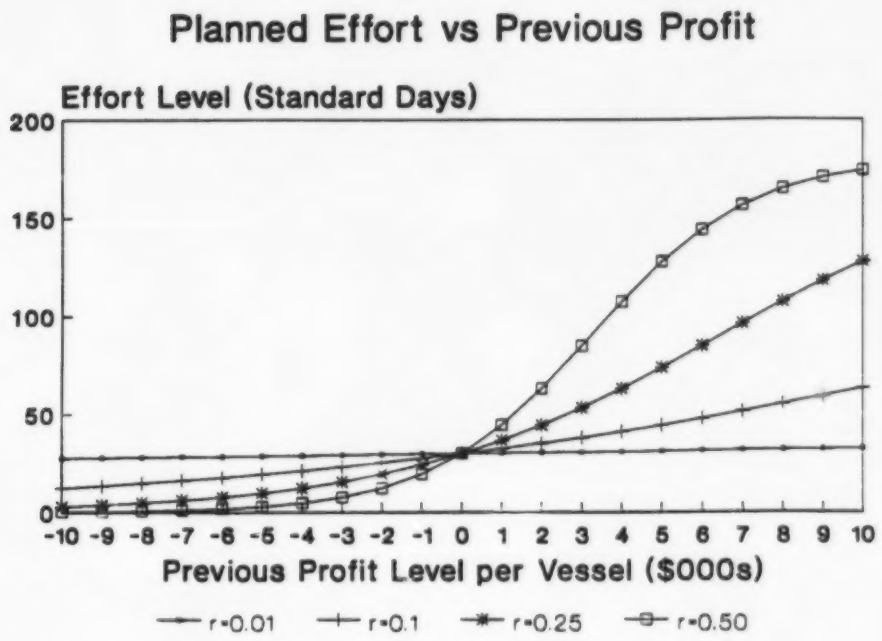

Figure 8a. r values are effort response factors.

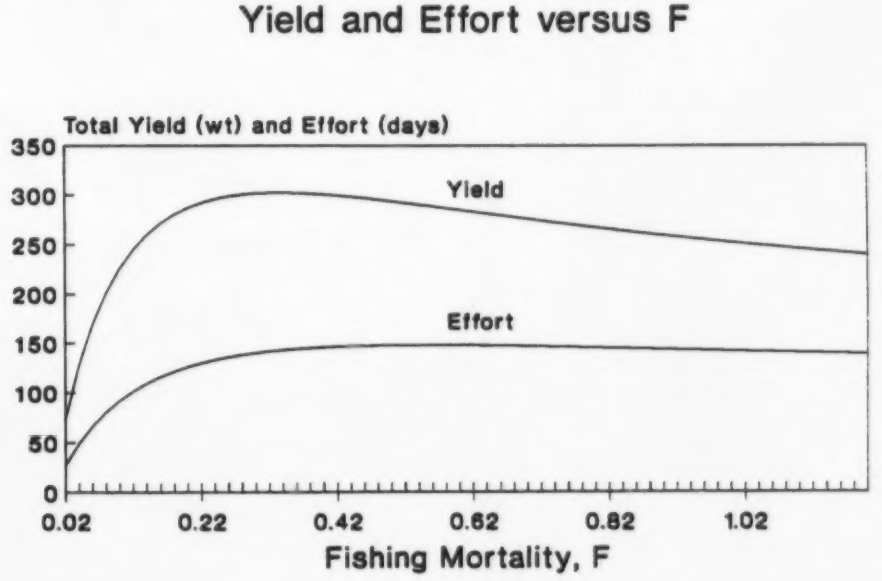

Figure 8b. Results are for fixed capital and catchability factors.

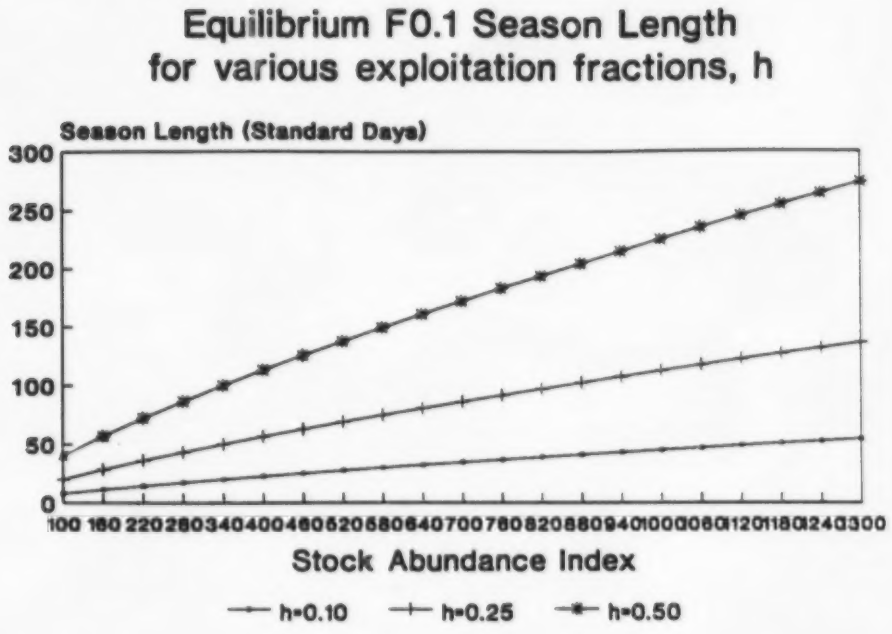

Figure 9a. Results are for fixed capital and catchability factors.

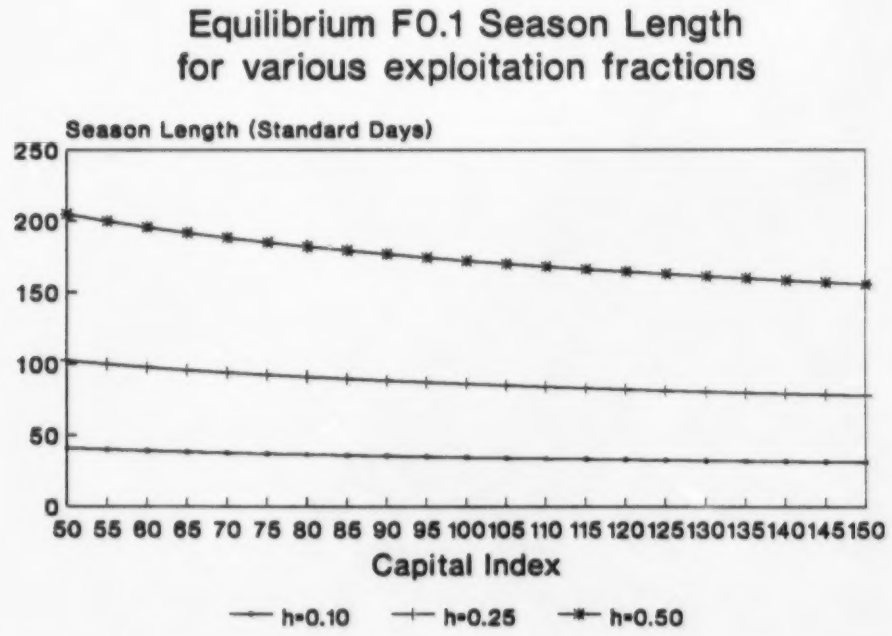

Figure 9b. Results are for fixed stock abundance and catchability factors.

Equilibrium Economic Returns versus F

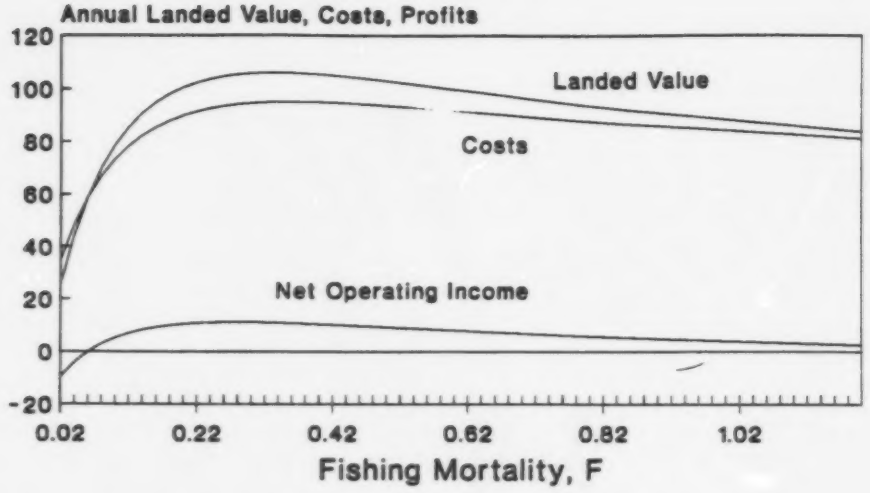

Figure 10a

Income Dynamics for F0.1 Policy

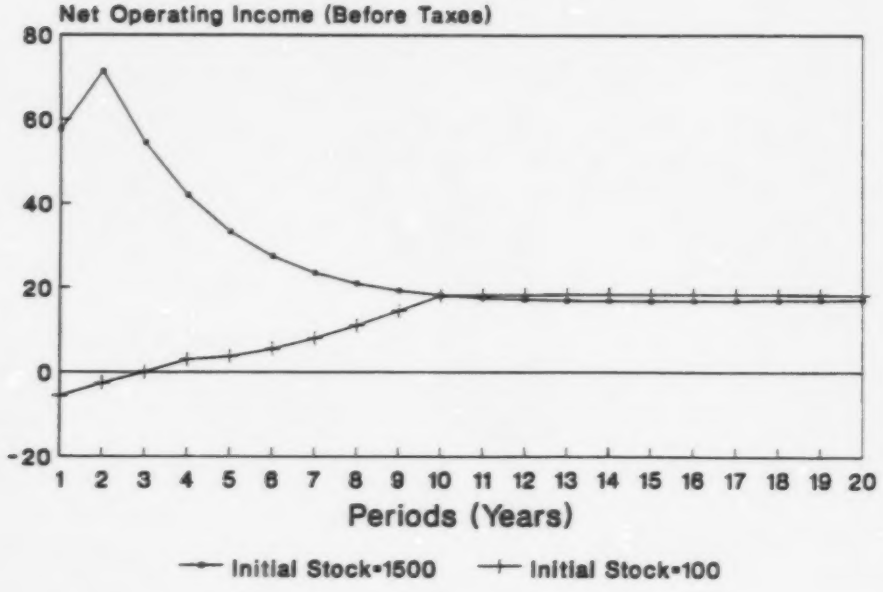

Figure 10b